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Modeling perennial groundcover effects on annual maize grain crop growth with the Agricultural Production Systems sIMulator

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Abstract

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Disciplines

Agriculture | Agronomy and Crop Sciences | Horticulture | Statistical Models

Comments

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MODELING PERENNIAL GROUNDCOVER EFFECTS ON ANNUAL MAIZE GRAIN CROP GROWTH WITH APSIM

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Abstract

The inclusion of perennial groundcover (PGC) in maize production offers a tenable solution to natural resources-related concerns associated with conventional maize; however, insight into system management and key information gaps is needed to guide future research. We therefore extended the Agricultural Production Systems sIMulator (APSIM) to an annual and perennial intercrop by integrating annual and perennial APSIM modules. These were parameterized for

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Kentucky bluegrass (KB) (*Poa pratensis* L.) or creeping red fescue (CF) (*Festuca rubra* L.) as PGC using a three-year dataset. Our objectives for this intercropping modeling study were to: i) simultaneously model a PGC and annual cash crop using APSIM software; ii) utilize APSIM to understand interactive processes in the maize-PGC system; and iii) utilize the calibrated model to explore both production and environmental benefits via scenario modeling. For objective I, the integrated model successfully predicted maize total aboveground biomass (TAB) (relative root mean square error, RRMSE of 13-27%) and PGC above- and belowground tissue N concentration (RRMSE of 11-18%). The calibrated model effectively captured observed trends in PGC biomass accumulation and soil nitrate (NO_3). For objective II, model analysis showed that competition for light was the primary maize yield penalty factor from PGC, while water and N impacted maize yield later in the maize growing season. In objective III, we concluded that effective PGC suppression produces minimal maize yield loss and significant environmental benefits; conversely, poor groundcover suppression may produce unfavorable environmental consequences and decrease maize grain yield. Effective PGC suppression is key for long-term system success.

Abbreviations: APSIM, Agricultural Production Systems sIMulator; CF, creeping red fescue; CGR, crop growth rate; KB, Kentucky bluegrass; LAI, leaf area index; MM, maize following maize; MMM, maize following two years of maize; PGC, perennial groundcover; RMSE, root mean square error; RRMSE, relative root mean square error; RUE, radiation use efficiency; SOC, soil organic C; SOM, soil organic matter; SWU, soil water uptake; TAB, total aboveground biomass.

Introduction

Annual grain crop production dominates the agricultural landscape, occupying approximately 70% of global cropland (Glover et al., 2010). On a global scale, two-thirds of world cropland is dedicated to maize (*Zea mays* L.) and only four other cereal crops (Leff et al., 2004). Cropland dedicated specifically to maize within the United States exceeds the cropland allotted to any of the other principal crops harvested (USDA, 2014). With the inclusion of maize stover as a feedstock for cellulosic biofuels production (Schnepf, 2013), the Renewable Fuel Standard mandate (USDOE, 2011) enhances economic incentives for the removal of maize stover from maize-based cropping systems. Using maize stover for livestock feed or bedding also becomes an attractive option when grain prices rise (Meteer, 2004).

In maize-based cropping systems, maize stover removal has negative ramifications for both soil fertility and long-term productivity (Blanco-Canqui and Lal, 2009; Rogovska et al., 2015). Crop residue adds organic carbon back to soils (Follett, 2001; Wilhelm et al., 2007), which is essential for maintaining adequate soil organic matter (SOM) (Wilhelm et al., 2004; Johnson et al., 2006), soil aggregation, and system stability (Tisdall and Oades, 1982). These structural features in turn affect water infiltration, hydraulic conductivity, and storage (Franzluebbers, 2001). Maize stover also shields topsoil from raindrop impact (Wilhelm et al., 2004). Maize stover removal exposes the soil surface; raindrop impact can thereby enhance soil erosion through the displacement of exposed soil particles (Pimentel et al., 1995). Much of the land that is used for maize production in the United States is highly erodible (Wilhelm et al., 2004). Soil erosion occurs at a rate several orders of magnitude above regeneration (Alexander, 1988; Montgomery, 2007), underscoring the importance of remedying soil depletion before agricultural productivity is affected on a broad scale. Natural resource degradation in conventional cropping systems therefore highlights the need for the development of alternative cropping systems, which can both (i) conserve natural resources and (ii) meet global demands for food, feed, fiber, and fuel.

The integration of PGC into annual grain crop operations is uniquely positioned to satisfy both of these cropping system goals. Perennial systems contribute to carbon sequestration, as increased land cover enhances soil carbon (Follett, 2001). Perennial systems therefore improve soil structure over annual cropping systems (Perfect et al., 1990), which also enhances water infiltration rates (Bharati et al., 2002). Additionally, perennial covers can substantially decrease NO_3 leaching (Sainju and Lenssen, 2011; Barsotti et al., 2013). An important advantage of integrating PGC into annual grain crop operations relates to utilizing the existing timing of operations. Myriad barriers to adoption exist for annual cover crops, including cost of adoption, a restricted planting window, and an additional encumbrance with termination (Dunn et al., 2016; Gonzalez-Ramirez et al., 2017). Activities such as strip tillage and chemical suppression in a PGC system, by contrast, may be coupled with existing management practices in an annual grain crop operation.

While the integration of PGC into an annual row crop system can mitigate the degradation of natural resources associated with certain production practices, reported maize grain yield from PGC systems is inconsistent, emphasizing the need for system refinement prior to deployment. Maize grain yield in a conventional system was reported as greater than maize grain yield with competitive intercropped PGC (Adams et al., 1970; Carreker et al., 1972; Robertson et al., 1976; Flynn et al., 2013; Bartel et al., 2017a; Bartel et al., 2017b), while it was elsewhere reported that maize grain yield was similar in both systems (Wiggans et al., 2012). Maize grain yield in intercropped PGC is often similar to the conventional system during the PGC establishment year (Scott et al., 1987; Abdin et al., 1997; Baributsa et al., 2008; Crusciol et al., 2013; Bartel et al., 2017a) as PGC competition with the maize crop is less than in PGC post-establishment years. Key system aspects contributing to these treatment effects and requiring further investigation include PGC and maize hybrid compatibility (Beale and Langdale, 1964), groundcover biomass accumulation, suppression effectiveness and duration (Elkins et al., 1979, 1983), and general system resiliency (Bartel et al., 2017b).

We therefore developed an APSIM simulation to address key components for PGC system management. Our objectives for this intercropping modeling study were to: i) modify APSIM to model this perennial and annual intercropped system; ii) utilize APSIM to understand interactive processes between the annual cash crop and PGC system; and iii) utilize the calibrated model to explore both production and environmental benefits via scenario modeling. Modeling can facilitate enhanced critical evaluation of the system and quantification of feedbacks within the system, guiding subsequent experimental research for faster system optimization.

While the thirty crop modules within APSIM include annual, perennial, and intercropping capabilities (Holzworth at al., 2014), the vast majority of APSIM simulations efforts thus far have modeled crop species on an individual basis. APSIM simulation models have thus far typically been used to simulate a single crop over a growing season of approximately four months in duration, and often forages for livestock systems in the case of perennials (Chichota et al., 2010; Moore et al., 2014; Pembleton et al., 2016; Ojeda et al., 2018; Teixeira et al., 2018). Simulating multiple growing seasons or crop rotations with and without annual cover crops is associated with enhanced complexity (Martinez-Feria et al., 2016; Puntel et al., 2016), and the simulation of annual and perennial intercropping aspects over multiple growing seasons involves robust complexity. This modeling endeavor is unique, as to our knowledge no prior study exists that models both perennial and annual species in an intercropped system. While not yet ready for widespread application, this study establishes the foundation to mechanistically model a complex annual-perennial system. Future researchers can build upon this work to further validate and expand our modeling concept to develop management practices and plant traits, augmenting both stability and consistency for system deployment.

Materials and Methods

Experiment data

The experiment design and many of the materials and methodologies used in this study were similar or identical to those included in related studies by Bartel et al. (2017a; 2017b). A three-site year study was conducted in successive years, in 2014, 2015, and 2016 for maize, maize following maize (MM), and maize following two years of maize (MMM) sequences, respectively, at the Agronomy and Agricultural Engineering Sorenson Research Farm (Boone), 11.9 km southeast of Boone, IA (42°0'N; 93°44'W). Climate data were obtained from the Iowa Environmental Mesonet station closest to the research site at NWS COOP site Ames-8-WSW, approximately 3 km northwest of Boone (Iowa Environmental Mesonet Network, 2017).

The experiment design consisted of a randomized complete block with three replications. The 9.14 m by 12.19 m research plots each accommodated twelve maize rows with 0.76-m interrow spacing. The APSIM data were collected from four of the 12 unique treatments per block with the same maize hybrid (Table 1). The no-PGC system with conventional tillage served as the control with maize stover residue retention. Maize stover residue was removed in an additional no-PGC system treatment with conventional tillage. The two groundcover treatments each included one species of PGC, either KB (Pennington Smart Seed KB blend, Madison, GA) 'Ridgeline', 'Wild Horse', 'Oasis', and 'Mallard' blend or CF (La Crosse Forage & Turf Seed LLC, La Crosse, WI) 'Boreal' with chemical suppression immediately after maize planting in the post PGC establishment years, zone tillage, and residue removal. The same maize hybrid, population insensitive DKC57-75RIB Blend, 107-day relative maturity, was used in all four treatments (Monsanto, St. Louis, MO; Monsanto, 2014). The hybrid is a drought tolerant, population insensitive variety with a recommended planting rate of medium to high.

Two 1.32-m rows of maize (each equivalent to 1.0 m^2 area) were harvested on 9 July at the V12 stage, 28 July at R1, 21 Aug. at R4, 1 Oct. at R6, and 15 Oct. at final harvest in 2015. Leaves were separated from stalks and dried at 70°C until a constant weight was achieved. Stalks and leaves were representatively subsampled and ground to pass a 1.0-mm sieve on a Wiley Mill (Model 4 Wiley Mill, Thomas Scientific, Swedesboro, NJ) and analyzed for C and N concentration using a vario Micro Cube Analyzer (Elementar Americas, Mt. Laurel, NJ). Six plants were representatively subsampled from the two 1.0 m^2 area maize harvested for leaf area index (LAI) estimation.

Soil samples were collected using a soil probe in both the spring at maize planting and fall at the maize R6 stage in both years to estimate belowground PGC biomass. Samples were taken at the 0- to 15-cm depth in 2015 at both collection dates and at the 0- to 15- and 15- to 30-cm depths in 2016 at both collection dates. Three samples were collected in each plot, each sample consisting of two probes of soil. One soil probe was taken within the drill row and one soil probe was taken in between two drill rows. An elutriator was used to wash soil from roots. Roots were dried in elutriation tubes at 60°C overnight. The contents of each elutriator tube were floated in water to remove soil from roots; roots were again dried at 60°C. Organic matter was then separated from roots and a dry weight was recorded for each plot after roots were dried at 60°C until a constant weight was achieved. The root mass obtained from each sample was used to estimate the root mass per treatment. Roots were ground to pass a 1.0-mm sieve on a UDY Cyclone Lab Sample Mill (UDY Corporation, Fort Collins, CO) and analyzed for C and N concentration using a vario Micro Cube Analyzer.

Photographs were taken of two 0.5-m^2 frames throughout the growing season in each plot with PGC to document groundcover persistence. Grasses were harvested on the same dates as corn harvests in 2015, and on 4 May, 28 June, 14 July, 26 July, and 4 Oct. in 2016. Tillers and stems were separated and counted, a fresh weight was recorded, and biomass was dried at 70°C until a constant weight was achieved. Tillers and stems were then ground to pass a 1.0-mm sieve on a UDY Cyclone Lab Sample Mill and analyzed for C and N concentration using a vario Micro Cube Analyzer.

Rainfall from April to October exceeded the 30-year average by 163 mm, 171 mm, 72 mm in 2014, 2015, and 2016, respectively, at the Boone research site. Rainfall was 102% greater than the 30-yr. trailing average in June 2014; a deficiency in early season precipitation was observed in June 2016, where rainfall was 81% less than the 30-yr. trailing average. The average monthly high and low air temperature did not depart substantially from the trailing 30-year averages during any of the three growing seasons.

Modeling calibration protocol

We utilized the APSIM (Keating et al. 2003; Holzworth et al., 2014) software framework version 7.9, which has capabilities of simulating intercropping systems. Modeling annual and perennial intercropping systems was informed by experiment data collected as outlined above. To our knowledge the majority of existing intercropping simulation studies have focused on the interactions between annual/cash crops and weeds early in the growing season or annual cover crops followed by an annual cash crop (Carberry et al., 1992; 1993; Martinez-Feria et al., 2016). Because no previous modeling example of a PGC and annual grain crop system was available, we had to conceptualize and build the simulation of PGC with an annual cash crop within APSIM. The following APSIM modules were utilized in this simulation: the Maize crop module (Keating et al., 2003), the Soybean

[*Glycine max* (L.) Merr.] crop module (Robertson and Carberry, 1998; Keating et al., 2003), a perennial warm season grass module called bambatsi (*Panicum coloratum* L.) (Huth, 2002); MICROMET module for the estimation of crop transpiration of competing crop canopies (Snow and Huth, 2004); Canopy, a necessary module for the instruction of intercropping within APSIM regarding competition for radiation (Carberry et al., 1996); the SoilWat module for soil water balance (Probert et al., 1998); the SoilN module which manages soil C and soil N mineralization, inorganic N and soil temperature modules jointly (Probert et al., 1998); and several management rules including planting, fertilizer, residue removal, and crop harvest (Keating et al., 2003; Holzworth et al., 2014).

Using APSIM management scripts, we defined a new (user-defined) parameter that describes the effectiveness of the herbicide application and duration of the summer suppression for PGC. We subsequently modified the APSIM source code to senesce green leaves in response to the herbicide application and therefore compiled a modified version of APSIM to use in this project. The management script and source code modifications are detailed in the supplementary materials. Figure 1 shows model behavior for different herbicide effectiveness scenarios. Emergent consequences in modeling by senescing leaves included a reduction in LAI and standing green biomass. We preferred to have herbicide effectiveness as an input parameter because field experience indicated that not all herbicides have the same effectiveness. All three herbicide application scenarios resulted in asymptotic behavior approaching 0 kg ha^{-1} new perennial aboveground biomass growth during the maize growing season. However, more time during the maize growing season was required to approach the horizontal asymptote after herbicide application with less effective PGC suppression, when less existing LAI is killed per day. The directed decomposition of the senesced PGC materials affected the N cycling as well as water balance via soil cover. The reduction in biomass due to herbicide application also affected the perennial plant height, a key variable in the intercropping simulation, as plant height has a major influence on light interception by the different species in a cropping system (Holt, 1995).

The APSIM simulation manages resource competition in an intercropping scenario between two crops by adjusting the allocation of radiation, water, and N (Keating et al., 2003). In reality, biotic factors may also be significantly impactful, but opportunity for the inclusion of biotic factors in modeling efforts is presently limited (Delincé, 2017).

We calibrated the APSIM maize module by adjusting cultivar-specific parameters to fit experiment data. Adjustments were made to the B_110 hybrid available in APSIM 7.9(Table 2). In the maize module, we increased radiation use efficiency (RUE) to a constant value of 1.8 g MJ^{-1} (Lindquist et al., 2005) that is more representative of modern elite hybrids in the USA. No further changes to the APSIM maize module were made.

The bambatsi module was utilized next in succession to simulate the intercropping aspects of the PGC system. The APSIM bambatsi module is representative of warm season plant species, requiring the re-parameterization of major crop parameters to represent our cool season PGC species. Major revisions to the crop module parameters were made to facilitate this conversion (Table 3). The light extinction coefficient for the cool season intercrop was significantly reduced, as well as the fraction of aboveground biomass allocated to the stem. The maximum root depth of the cool season PGC species in our experiment was shallower than the default root depth associated with warm season bambatsi grass. The cool season grass intercrop was made much more frost resistant than the default frost resistance for bambatsi. The length of the photoperiod was extended and the maximum leaf senescence rate due to stress was increased. Finally, the root N concentration was increased. The RUE for fescue was greater than the RUE for KB. These changes were guided by experiment data and expert opinion.

To explore the impact of PGC on productivity and environmental sustainability we performed a scenario analysis in which we ran the model for 20 consecutive years and calculated yields, N leaching, and soil organic matter changes. Results were analyzed using probability plots (Figure 7).

Statistical Analysis

The prediction accuracy and model goodness of fit for each of the modeled parameters were evaluated by both graphical representations of observed and predicted values and statistical analysis appropriate for nonlinear crop modeling (Archontoulis and Miguez, 2015). Statistical analysis included calculating the root mean square error (RMSE) and RRMSE for each of the modeled parameters (Wallach, 2006). In this study, we considered an RRMSE ≤ 15% as “good” agreement; 15–30% as “moderate” agreement; and ≥ 30% as “poor” agreement (Liu et al., 2013; Puntel et al., 2016)”

Results and Discussion

Objective 1 – APSIM calibration results

Maize biomass production

The model effectively captured the reduction in maize TAB in the PGC systems observed in our field study (Figure 2). The CF caused a greater decline in maize TAB for maize with intercropped CF compared to maize with intercropped KB during the calibration process. The CF produced greater

PGC biomass than the KB, and thereby increased competition for the maize with intercropped CF for water, light, and nutrients (Kropff and van Laar, 1993). The reduction in the maize crop growth rate (CGR) began early and accumulated over the maize growing season, emphasizing the need for effective suppression of the PGC.

During the three-year calibration period the model predicted well maize TAB with a RRMSE and RMSE of 1,929 kg ha^{-1} and 13%, respectively, for conventional maize with residue retention as the control, 1,852 kg ha^{-1} and 14%, respectively, for maize with intercropped KB, and 2,682 kg ha^{-1} and 27%, respectively, for maize with intercropped CF (Figure 2).

The reduction in the maize CGR is consistent with exacerbated crop yield losses after the onset of weed competition when weed control is delayed (Hartzler, 2009). The trend in CGR reduction in our simulation reflects the well-documented importance of effective weed suppression as a fundamental management operation to support maize yield prior to the critical period for weed control, when the maize shade avoidance response is triggered regardless of resources abundance (Page et al., 2009).

Soil nitrate concentration

In terms of N dynamics both measurements and simulations (0- to 5- and 5- to 15-cm depths) showed few differences in the soil NO_3 concentration between the three maize systems at a fixed N application of ~190 kg N ha^{-1}, reflecting our field study N application rate. The simulation indicated low soil NO_3 in the PGC system (Figure 3), reflecting an N limitation to PGC growth and biomass production early in spring and later in the fall. The maize crop was not limited by N at the maize grain yield levels of ~7 to 12 Mg ha^{-1} recorded during our field study, which represent low to average maize grain yield levels in Boone County, IA, USA (USDA NASS, 2018). Maize nutrient recommendations are largely determined for monoculture sequences of maize following maize or maize following a legume (i.e., soybean or alfalfa) in the Midwest (Camberato et al., 2005; Sawyer et. al, 2006), reflecting customary crop rotations in this region. Nitrogen dynamics in maize-perennial groundcover systems require further research and present an opportunity for future modeling work.

The model captured the general seasonal trends in NO_3 as influenced by soil microbial nitrification, but poorly simulated specific soil NO_3 concentration (mg L^{-1}) over the three-year calibration period for conventional maize with residue retention as the control, maize with intercropped KB, and maize with intercropped CF with a RRMSE of 270% and RMSE of 39 mg L^{-1} NO_3 at the 0- to 5-cm soil depth and RRMSE of 106% and RMSE of 8 mg L^{-1} NO_3 at the 5- to 15-cm soil depth (Figure 3).

The N limitation for the PGC is consistent with documented soil N unavailability to support early spring cool season grass growth and fall root regeneration following summer dormancy and root decomposition (Hull, 1999). To supply the maize crop with a non-yield limiting N rate as an N responsive crop, maize intercropped with a PGC may require a tailored N rate recommendation and specific nutrient application method to support greater maize grain yield levels. For example, similar maize grain yield was reported between maize with intercropped perennial cover with paraquat application, strip tillage, and point-injector N fertilizer application and the control (Wiggans et al., 2012).

Perennial groundcover biomass (kg ha^{-1}) and tissue N concentration (%)

The model captured most of the PGC above- and belowground biomass dynamics, with some exceptions. There was underestimation in the simulated CF biomass; the RMSE and RRMSE for both the KB and CF PGC belowground biomass is disproportionately augmented by the underestimation specifically in the 4 May 2016 collection date (Figure 4). Model calibration to fit observed CF aboveground biomass values reduced simulated maize grain yield to values less than reported in our field study for the maize with intercropped CF. The significant variability of the recorded field data is evident in the standard errors in belowground biomass measurements (Figure 4). Additionally, Figure 3 reflects the directionally correct simulation of soil NO_3. When considering both the variability and directionally correct soil NO_3 simulation to evaluate model performance against measured data, our model cohesively represents soil-plant N dynamics in this system.

PGC above- and belowground tissue N concentration were simulated well over three years, with a RRMSE of 11% and RMSE of 0.004% N for KB aboveground leaf tissue N concentration (Figure 4). The model simulated KB belowground biomass root tissue N concentration with a RRMSE of 13% and RMSE of 0.002% N (Figure 4). The model simulated CF aboveground green leaf tissue N concentration with a RRMSE of 11% and RMSE of 0.003% N. The model simulated CF belowground biomass root tissue N concentration with a RRMSE of 18% and RMSE of 0.003% N (Figure 4).

The model simulated poorly KB above- and belowground biomass (kg ha^{-1}) over three years with a RRMSE of 43% and RMSE of 90 kg ha^{-1} for aboveground biomass and a RRMSE of 65% and RMSE of 573 kg ha^{-1} for belowground biomass (Figure 4). The model similarly simulated CF above- and belowground biomass (kg ha^{-1}) during the same period with a RRMSE of 86% and RMSE of 617 kg ha^{-1} for aboveground biomass and a RRMSE of 61% and RMSE of 746 kg ha^{-1} for belowground biomass (Figure 4).

The model simulated observed trends in seasonal variability with above- and belowground biomass production and tissue N dynamics, capturing biomass production and its dynamic distribution between shoots and roots effectively. Simulated PGC biomass followed the expected bimodal perennial growth pattern (Hull, 1999). Shoot and root biomass declined after spring herbicide application and during summer suppression prior to fall regrowth (Figure 4).

The simulated results indicate a greater level of accuracy for aboveground biomass accumulation than belowground biomass accumulation for KB. This is unsurprising given the greater uncertainty that exists with root measurements than aboveground biomass measurements (Ordonez et al., 2018) and also uncertainties in modeling root biomass (Ebrahimi-Mollabashia et al., 2019). These results indicate an enhanced sensitivity to the PGC in the simulated maize grain yield over the maize grain yield values recorded in our field study, even with the rapid post-suppression recovery of the PGC observed in our field study (Bartel et al., 2017b). The enhanced effect of PGC biomass production in the simulation on end of season maize biomass is likely attributable to how well we can represent the spatial distribution of the crops within the model. A uniform PGC is assumed within APSIM, in contrast to the 38-cm width mechanical strip tillage that was performed in the PGC for seed bed preparation and crop row establishment prior to spring maize planting in our field study. Flynn et al. (2013) reported that maize plants spaced farther away from PGC exhibited better growth and development. Strip tillage width presents another area for future research, as effective strip tillage width may be dependent on PGC species and rapidity of post-suppression recovery. Further measurements are needed to expand the current modeling capacity to better represent the system and soil water-nitrogen-carbon dynamics.

Maize grain yield and total aboveground biomass

The model captured dynamics and trends in treatment responses for both maize grain yield and maize TAB during the three-year calibration period (Figure 5). However, the model generally underestimated the average simulated effect of both PGC species on maize grain yield during the three-year calibration period (Figure 5). The reason for this underestimation is likely two-fold: a) the model cannot model biotic stress factors that were probably impactful; b) the model assumed a uniform plant density for the maize crop, while in the research plots we measured variability in maize plant density. Overall our simulation showed that residue removal enhanced yield in the conventional maize system over the three-year period, and the CF PGC species generally produced the greatest average maize yield reductions compared to the control. The calibrated model simulation was in agreement with the greater maize grain yield penalty observed in the post-groundcover establishment years in our field study (Figure 5), particularly with CF. The enhanced impact of greater perennial biomass accumulation on maize grain yield is likely caused by induction of the maize shade avoidance response and the larger fescue root mass that enhances competition with the maize for abiotic resources.

Compared to the control maize with residue retention, average maize grain yield was 7 and 4% greater with residue removal for measured and simulated values, respectively. Average maize TAB was 6 and 3% greater with residue removal for measured and simulated values, respectively, than the control with residue retention. These results are consistent with findings that maize residue removal increases maize yield in the short term in the upper Midwest, particularly during periods of excess or deficient moisture; however, a net long-term decline in soil quality through enhanced soil erosion and SOM loss is expected (Rogovska et al., 2016).

Average measured reductions in maize grain yield compared to the control were -20 and -30% for maize with intercropped KB and maize with intercropped CF, respectively. Average simulated reductions in maize grain yield compared to the control were -5 and -19% for maize with intercropped KB and maize with intercropped CF, respectively. The model underestimated the impact of KB on average simulated maize TAB at -8% from the control compared to the average measured difference from the control of -20%. The model slightly overestimated the impact of CF on average simulated maize TAB in the CF at -27% from the control compared to the average measured difference from the control of -19%.

It is important to note that our model simulation involved one maize hybrid. A significant maize hybrid by PGC species interaction was reported for several measured maize parameters in maize with intercropped PGC (Bartel et al., 2017b), documenting the disparity in maize germplasm response to PGC species. For example, a yield stable maize hybrid may have better yield response to an aggressive PGC than other maize varieties; conversely, maize germplasm which responds positively to enhanced nutrient availability will be advantageous when intercropped with adequately suppressed or summer dormant perennial grass species. In our field studies we additionally reported a reduction in productivity in the second-year maize with residue retention (Bartel et al., 2017b). Autotoxicity, a specific type of allelopathy, may be one of several factors that contribute to the continuous maize yield penalty (Maloney et al., 1999). New maize germplasm should be considered in each maize rotation to avoid an autotoxicity-related yield penalty. A need thusly exists for further research regarding maize hybrid-PGC species compatibility and maize plant germplasm response to PGC in maize-PGC systems.

Objective 2 – Modeling insights to understand the system

The model analysis showed that competition for radiation was the primary maize yield penalty factor from PGC. Water and N were responsible for maize yield consequences later in the maize growing season.

Soil water uptake (SWU) from the 0- to 45-cm soil layer, N uptake from the 0- to 45-cm soil layer, and CGR (kg ha^{-1} d^{-1}) were simulated for conventional maize with residue retention as the control, maize with intercropped KB, maize with intercropped CF, and either KB or CF alone (Figure 6). Maize radiation interception (MJ m^{-2} d^{-1}) was simulated for the maize in all three maize systems (Figure 6). Simulations for 2015 began during the initial PGC bimodal growth curve on 1 Apr., prior to maize planting, and ended on 27 Oct. after maize harvest.

The simulated radiation interception (MJ m^{-2} d^{-1}) reflects the well-documented daily inconsistency in available radiation for crop interception (Fisher, 2003). The simulated daily maize radiation interception for maize with intercropped CF was the least of all three maize systems, with a marked early season decrease compared to other systems. From 23 May until 14 July 2015, the average radiation interception for maize with intercropped CF was 86.1% less than control maize. We identified 23 May as the start of positive simulated values for maize radiation interception, while 14 July represents the staging date at which the maize in our field study likely approached the end of the critical period for weed control at V12 (Bartel et al., 2017b). The control maize, maize with intercropped KB, and maize with intercropped CF averaged 3.9, 2.5, and 0.5 MJ m^{-2} d^{-1}, respectively, during this period.

Peak simulated PGC SWU and N uptake occurred in the spring after maize planting. Maximum KB and CF SWU were 2.6 mm d^{-1} on 22 May and 3.4 mm d^{-1} on 28 May, respectively. Maximum KB and CF N uptake were 2.0 mm d^{-1} on 22 May and 5.0 mm d^{-1} on 19 May, respectively. These peak soil water and nutrient uptake dates agree with the timing of the maximum CGR for the perennial groundcovers, on 21 May at 179.9 and 156 kg $ha^{-1}d^{-1}$ for KB and CF, respectively. Perennial groundcovers under maize continued to take up less N and soil water levels during summer dormancy until fall regrowth began, when N uptake and SWU levels increased during the latter bimodal growth curve after maize harvest and removal. The CF continued to transpire to a greater extent during the summer and later into the season than KB, as evidenced by the greater SWU for CF. Simulated maize SWU and N uptake values were correspondingly least for maize intercropped with CF (peaking at 5.0 mm d^{-1} on 18 Jul. and 5.8 mm d^{-1} on 14 Jul., respectively).

Soil water, soil N, and radiation interception are three significant factors that affect CGR and correspondingly influence the simulated CGR in APSIM, as indicated by the yellow arrows connecting soil water, soil N, and radiation interception to CGR in Figure 6. Crop growth rate is highly impactful on maize grain sink strength, as CGR influences both maize kernel number (Vega et al., 2001) and yield (Christy et al., 1982) as a light-limited C4 plant. The simulated CGR reflects dry matter accumulation on a daily basis (kg ha^{-1} d^{-1}) for all crops in the system. The daily CGR was greater for conventional maize with residue retention than maize with either intercropped PGC species. While effects are similar from both perennial groundcovers on the intercropped maize, there existed a greater decrease in early season maize CGR for the maize with intercropped CF. The general trends for the simulated maize CGR closely track simulated maize radiation interception trends over the growing season between systems (Figure 6). Where CF competed for and captured radiation which the maize crop needed, maize CGR was largely obstructed and never recovered from the early season CGR deficit that CF caused. This is consistent with the documented inability of maize to recapture lost biomass production from early season stresses (Pagano et al., 2007).

Objective 3 – Modeling scenario

To contribute to system optimization, we performed for the first time a scenario analysis to quantify expected long-term outcomes associated with this perennial system. We leveraged the modeling capacity that we built to extrapolate three years of data to a 20-year simulation. We found:

i. KB was a better PGC in maize systems than CF;

ii. When maize with intercropped PGC is managed with adequate PGC suppression duration and herbicide effectiveness, the maize yield loss is minimal and the environmental benefits are significant (esp. reduced runoff and NO_3 leaching);

iii. While the environmental benefits are conspicuous when PGC is managed with adequate suppression duration and herbicide effectiveness, a poorly suppressed groundcover produces unfavorable environmental consequences and a greater environmental footprint in addition to suppressing maize yield. Maize grain is the largest sink for soil nitrate incorporated into the maize plant; up to 95% of the N found in maize grain is remobilized from leaves during leaf senescence (Xu et al., 2012). If maize CGR and plant biomass accumulation are reduced, the maize will correspondingly take up less soil water and soil NO_3 (Figure 6A, Figure 6B). As PGC is also stunted by inadequate suppression in these scenarios, uptake of soil water and soil NO_3 by the partially-suppressed PGC cannot compensate for the reduction in soil NO_3 consumption by the maize. The NO_3 from soil microbial nitrification and fertilizer application not taken up by the maize row crop will then leach out of the soil (7B).

We ran five simulations from 31 Dec. 1996 to 31 Dec. 2016, with maize planted on 16 May each year. Our cropping systems included continuous maize with residue retention as the control, two continuous maize scenarios with intercropped KB, and two continuous maize scenarios with intercropped CF. Maize residue was removed in all intercropped PGC scenarios. An herbicide effectiveness of 0.5 was applied in all four perennial intercrop scenarios. However, our PGC treatments included two suppression durations for both groundcover species. In one Kentucky Bluegrass (BG) and one creeping red fescue (FE) scenario, the suppression period was applied from 10 May to 5 Sept. In the other Kentucky Bluegrass (BG1) and creeping red fescue (FE1) scenarios, the PGC suppression period had a delayed onset of 5 Jun. and ended earlier on 25 Aug.

Both perennial groundcovers (BG and FE) with suppression from 10 May to 5 Sept. reduced runoff, reduced N leaching, and increased soil organic carbon (SOC) compared to the control (Table 4). The Kentucky bluegrass (BG) and creeping red fescue (FE) with suppression from 10 May to 5 Sept. produced maize yield which was only -3 and -5% less than the control.

Additionally, we multiplied SOC by a conversion factor of 1.724 to estimate SOM in all five systems (Table 4). We acknowledge that variation exists for this broadly adopted conversion factor, contingent on soil type, and organic matter C content can vary from 58% C (Howard, 1965). An increase in SOM was simulated for BG and FE of 1.0 and 1.7%, respectively, compared to the control. This is consistent with the greater expected SOC accumulation resulting from greater CF biomass accumulation.

We observed in our field studies that groundcovers with rapid post-suppression recovery reduced maize grain yield (Bartel et al., 2017b). A stark contrast was observed between the PGC treatment effects for the extended suppression period of 10 May to 5 Sept. and the abbreviated suppression period of 5 Jun. to 25 Aug. Less annual runoff was produced compared to the control with either groundcover and for either suppression period (Figure 7A). However, not only was maize yield least in the BG1 and FE1 scenarios out of all five maize systems at -16 and -41%, respectively, compared to the control (Figure 7C), the environmental footprint was greatest in these groundcover systems. The BG1 and FE1 scenarios increased N leaching by 152 and 281%, respectively, and reduced SOC by -0.2 and -0.3%, respectively, compared to the control maize treatment (Figure 7B, Figure 7D, Table 4).

Faster green up of the PGC in the spring is advantageous for NO_3 recycling to diminish nitrate leaching. Our simulation findings, however, underscore the importance of early-season PGC suppression for both maize production and environmental consequences.

Conclusions

When adequate PGC suppression is achieved in maize with intercropped PGC, the maize yield loss is minimal and the environmental benefits are significant; conversely, a poorly suppressed groundcover may produce unfavorable environmental consequences in addition to suppressing maize grain yield. This simulation is an initial analysis of a PGC and annual maize intercropping system. Additional study-years and measurements are necessary to develop a robust modeling framework to comprehensively simulate this complex system. This paper thusly provides context and direction to future researchers about the field data and parameters which need to be collected to fully calibrate this modeling system, as well as inform management decisions for a PGC cover and annual maize intercropping system, based on maize yield response to perennial grass biomass accumulation.

Because of a paucity of basic agronomic data on bluegrass and fescue in the literature, we posited several assumptions in this work guided by expert opinion. With these informed assumptions, the model performed well and generally agreed with most of the experiment observations, providing further insight to system behavior and environmental implications. Basic fundamental research such as RUE, light extinction coefficient, and root distribution in the soil profile of this intercropping system is required to more thoroughly understand the mechanisms which influence system performance. Model accuracy will improve with field measurements which can be input as concrete values for cool season groundcover parameterization.

More research is required to optimize the system for consistency before broad adoption and implementation at the farm level. Such research areas include maize hybrid-perennial groundcover species compatibility, maize germplasm response, N rate recommendation and specific nutrient application method, and strip tillage width in maize-perennial groundcover systems. Additionally, the results emphasize that a research priority must include effective PGC suppression to manage perennial cover growth and perennial cover biomass accumulation around the critical early season periods for maize growth.

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References

Abdin, O.A., B.E. Coulman, D. Coultier, M.A. Faris, and D.L. Smith. 1997. Establishment, development and yield of forage legumes and grasses as cover crops in grain maize in eastern Canada. J. Agron. Crop Sci. 179:19–27. doi:10.1111/j.1439-037X.1997.tb01143.x

Adams, W.E., J.E. Pallas, and R.N. Dawson. 1970. Tillage methods for corn-sod systems in the Southern Piedmont. Agron. J. 62:646–649.

Alexander, E.B. 1988. Rates of soil formation: Implications for soil-loss tolerance. Soil Sci. 145:37–45. doi:10.1097/00010694-198801000-00005

Archontoulis, S.V., and F.E. Miguez. 2015. Nonlinear Regression Models and Applications in Agricultural Research. Agron. J. 107: 786-798.

Baributsa, D.N., E.F. Foster, K.D. Thelen, A.N. Kravchenko, D.R. Mutch, and M. Ngouajio. 2008. Maize and cover crop response to maize density in an interseeding system. Agron. J. 100:981–987. doi:10.2134/agronj2007.0110

Barsotti, J.L., U.M. Sainju, A.W. Lenssen, C. Montagne, and P.G. Hatfield. 2013. Net greenhouse gas emissions affected by sheep grazing in dryland cropping systems. Soil Sci. Soc. Am. J. 77:1012-1025.

Bartel, C.A., C. Banik, A.W. Lenssen, K.J. Moore, D.A. Laird, S.A. Archontoulis, K.R. Lamkey. 2017a. Living mulch for sustainable maize stover biomass harvest. Crop Sci. 57:3273–3290.

Bartel, C.A., C. Banik, A.W. Lenssen, K.J. Moore, D.A. Laird, S.A. Archontoulis, K.R. Lamkey. 2017b. Establishment of perennial groundcovers for maize-based bioenergy production systems. Agron. J. 109:822–835.

Beale, O.W., and G.W. Langdale. 1964. The compatibility of corn and coastal bermudagrass as affected by tillage methods. J. Soil Water Conserv. 19:238–240.

Bharati, L., K.-H. Lee, T.M. Isenhart, and R.C. Schultz. 2002. Soil water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. Agrofor. Syst. 56:249–257.

Blanco-Canqui, H., and R. Lal. 2009. Corn stover removal for expanded uses reduces soil fertility and structural stability. Soil Sci. Soc. Am. J. 73:418–426.

Carberry, P.S., B.A. Keating, and R.L. McCown. 1992. Competition between a crop and undersown pasture - simulations in a water-limited environment. Pages 206-209 in Proceedings of the Sixth Australian Agronomy Conference, Australian Society of Agronomy, Parkville, Victoria, Australia.

Carberry, P.S., R.L. McCown, and N. de Groot. 1993. Can profitable cropping systems be developed in the semi-arid tropics of northern Australia? Pages 236-239 in Proceedings of the Seventh Australian Agronomy Conference. Australian Society of Agronomy, Parkville, Victoria, Australia.

Carberry, P.S., S. Adiku, R.L. McCown, and B.A. Keating. 1996. Application of the APSIM cropping systems model to intercropping systems. In: Ito, C., Johansen, C., Adu-Gyamfi, K., Katayama, K., Kumar-Rao, J.V.D.K., Rego, T.J. (Eds.), Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-arid Tropics, pp. 637e648.

Camberato, J., S. Culman, D. Kaiser, C. Laboski, E. Nafziger, J. Sawyer, and K. Steinke. Corn nitrogen rate calculator. Iowa State University Extension and Outreach, Ames, Iowa, 2005. Last modified 2018. http://cnrc.agron.iastate.edu (accessed 19 Mar 2019).

Carreker, J.R., J.E. Box, R.N. Dawson, E.R. Beaty, and H.D. Morris. 1972. No-till corn in fescuegrass. Agron. J. 64:500–503.

Cichota, R., I. Vogeler, V.O. Snow, and M. Shepherd. 2010. Modelling the effect of a nitrification inhibitor on N leaching from grazed pastures. Proceedings of the New Zealand Grassland Association 72, 43-47.

Crusciol, C.A.C., A.S. Nascente, G.P. Mateus, E. Borghi, E.P. Leles, and N.D. Santos. 2013. Effect of intercropping on yields of corn with different relative maturities and palisadegrass. Agron. J. 105:599–606. doi:10.2134/agronj2012.0426

Delincé, J. 2017. Recent practices and advances for AMIS crop yield forecasting at farm/parcel level: A review. FAO-AMIS Publication: Rome.

Dunn, M., J.D. Ulrich-Schad, L.S. Prokopy, R.L. Myers, C.R. Watts, and K. Scanlon. 2016. Perceptions and use of cover crops among early adopters: Findings from a national survey. J Soil Water Conserv. 71:29–40.

Ebrahimi-Mollabashia, E., N.I. Huth, D.P. Holzwoth, R.A. Ordóñez, Jerry L. Hatfield, Isaiah Huber, Michael J. Castellano, Sotirios V. Archontoulis. 2019. Enhancing APSIM to simulate excessive moisture effects on root growth. Field Crop Res. 236:58-67. doi:10.1016/j.fcr.2019.03.014

Elkins, D., D. Frederking, R. Marashi, and B. McVay. 1983. Living mulch for no-till corn and soybeans. J. Soil Water Conserv. 38:431–433.

Elkins, D.M., J.W. Vandeventer, G. Xapusta, and M.R. Anderson. 1979. No-tillage maize production in chemically suppressed grass sod. Agron. J. 71:101–105. doi:10.2134/agronj1979.00021962007100010026x

Follett, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res. 61:77–92.

Fisher, T.R., A.B. Gustafson, G.M. Radcliffe, K.L. Sundberg, and J.C. Stevenson. 2003. Estuaries 26(6):1450-1460. https://doi.org/10.1007/BF02803653

Flynn, E.S., K.J. Moore, J.W. Singer, and K.R. Lamkey. 2013. Evaluation of grass and legume species as perennial ground covers in maize production. Crop Sci. 53:611–620.

Franzluebbers, A.J. 2001. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil Tillage Res. 66:197–205.

Gentry, L.F., M.L. Ruffo, and F.E. Below. 2013. Identifying factors controlling the continuous corn yield penalty. Agron. J. 105:295–303. doi:10.2134/agronj2012.0246

Glover, J.D., J.P. Reganold, L.W. Bell, J. Borevitz, E.C. Brummer, E.S. Buckler, C.M. Cox, T.E. Crews, S.W. Culman, L.R. DeHaan, D. Eriksson, B.S. Gill, J. Holland, F. Hu, B.S. Hulke, A.M.H. Ibrahim, W. Jackson, S.S. Jones, S.C. Murray, A.H. Paterson, E. Ploschuk, E.J. Sacks, S. Snapp, D. Tao, D.L. Van Tassel, L.J. Wade, D.L. Wyse, and Y. Xu. 2010. Increased food and ecosystem security via perennial grains. Science 328:1638–1639.

Gonzalez-Ramirez, M.J., C.L. Kling, J.G. Arbukle, L.W. Morton, J. McGuire, C. Ingels, and J. Benning. 2017. Cover crop adoption decisions in Iowa: insights from an in-person survey. Agriculture Policy Review. Iowa State University.

Hartzler, R.G. Early-season weed competition in corn. 2009. Iowa State Research Farm Progress Reports. 582. http://lib.dr.iastate.edu/farms_reports/582

Holt, J.S. 1995. Plant responses to light: A potential tool for weed management. Weed Sci. 43:474-482.

Holzworth, D.P., N.I. Huth, P.G. deVoil, E.J. Zurcher, N.I. Herrmann, G. McLean, K. Chenu, E.J. van Oosterom, V. Snow, C. Murphy, A.D. Moore, H. Brown, J.P.M. Whish, S. Verrall, J. Fainges, L.W. Bell, A.S. Peake, P.L. Poulton, Z. Hochman, P.J. Thorburn, D.S. Gaydon, N.P. Dalgliesh, D. Rodriguez, H. Cox, S. Chapman, A. Doherty, E. Teixeira, J. Sharp, R. Cichota, I. Vogeler, F.Y. Li, E. Wang, G.L. Hammer, M.J. Robertson, J.P. Dimes, A.M. Whitbread, J. Hunt, H. van Rees, T. McClelland, P.S. Carberry, J.N.G. Hargreaves, N. MacLeod, C. McDonald, J. Harsdorf, S. Wedgwood, and B.A. Keating. 2014. APSIM evolution towards a new generation of agricultural systems simulation. Environ. Modell. Softw. 62:327-350. https://doi.org/10.1016/j.envsoft.2014.07.009

Howard, P.J.A. 1965. The carbon-organic matter factor in various soil types. Oikos 15:229-236. DOI: 10.2307/3565121

Hull, R.J. 1999. Winter/spring nutrient use by cool- and warm-season turf. In Turfgrass Trends: 11-15.

Huth, N.I., P.S. Carberry, P.L., Poulton, L.E. Brennan, and B.A. Keating. 2002. A framework for simulating agroforestry options for the low rainfall areas of Australia using APSIM. Eur. J. Agron. 18:171-185.

Iowa Environmental Mesonet Network. 2017. National Weather Service Cooperative Observer Program. Iowa Environ. Mesonet Network. https://mesonet.agron.iastate.edu/COOP/ (accessed 8 Mar 2017).

Jalota, S.K., B.B. Vashisht, S. Sharma, and S. Kaur. 2018. Emission of greenhouse gases and their warming effect. In Understanding climate change impacts on crop productivity and water balance. Academic Press, San Diego, CA. https://doi.org/10.1016/B978-0-12-809520-1.00001-X (accessed 7 Mar 2019).

Johnson, J.M.F., R.R. Allmaras, and D.C. Reicosky. 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. Agron. J. 98:622–636.

Karlen, D.L., G.E. Varvel, J.M.F. Johnson, J.M. Baker, S.L. Osborne, J.M. Novak, P.R. Adler, G.W. Roth, and S.J. Birrell. 2011. Monitoring soil quality to assess the sustainability of harvesting maize stover. Agron. J. 103:288–295.

Keating, B. A., P.S. Carberry, G.L. Hammer, M.E. Probert, M.J. Robertson, D. Holzworth, N.I. Huth, J.N.G. Hargreaves, H. Meinke, Z. Hochman, G. McLean, K. Vergurg, V. Snow, J.P. Dimes, M. Silburn, E. Wang, S. Brown, K.L. Bristow, A. Asseng, S. Chapman, R.L. McCown, D.M. Freebairn, and C.J. Smith. 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18:267-288. https://doi.org/10.1016/S1161-0301(02)00108-9

Knezevic, S.Z., S.P. Evans, E.E. Blankenship, R.C. Van Acker, and J.L. Lindquist. 2002. Critical period for weed control: The concept and data analysis. Weed Sci. 50:773–786.

Kropff, M. J., and H.H. van Laar. 1993. Modelling crop-weed interactions. Wallingford, U.K.: CAB International and Manila, Philippines: International Rice Research Institute.

Leff, B., N. Ramankutty, and J.A. Foley. 2004. Geographic distribution of major crops across the world. Global Biogeochem. Cycles 18 GB1009. doi:10.1029/2003GB002108

Licht, M., R. Elmore, and L.J. Abendroth. 2001. Maize planting guide. PM 1885. Iowa State Univ. Ext., Ames.

Liebman, M., L.R. Gibson, D.N. Sundberg, A.H. Heggenstaller, P.R. Westerman, C.A. Chase, R.G. Hartzler, F.D. Menalled, A.S. Davis, and P.M. Dixon. 2008. Agronomic and economic performance characteristics of conventional and low-external-input cropping systems in the central Corn Belt. Agron. J. 100:600–610.

Lindquist, J.L., T.J. Arkebauer, D.T. Walters, K.G. Cassman, and A. Dobermann. 2005. Maize radiation use efficiency under optimal growth conditions. Agron. J. 97:72–78.

Liu, S., Yang, J. Y., Zhang, X. Y., Drury, C. F., Reynolds, W. D., and Hoogenboom, G. (2013). Modelling crop yield, soil water content and soil temperature for asoybean– maize rotation under conventional and conservation tillage systems in Northeast China. Agric. Water Manage. 123, 32–44. doi: 10.1016/j.agwat.2013.03.001

Maloney, T.S., K.G. Silveira, and E.S. Oplinger. 1999. Rotational vs. nitrogen-fixing influence of soybean on corn grain and silage yield and nitrogen use. J. Prod. Agric. 12:175–187.

Martinez-Feria, R.A., R. Dietzel, M. Liebman, M.J. Helmers, and S.V. Archontoulis. 2016. Rye cover crop effects on maize: a system-level analysis. Field Crops Res. 196:145–159.

Meteer, T.W. 2014. New uses of stover: Stalklage as alternative forage. In: Proceedings of the Driftless Region Beef Conference, Dubuque, IA. 30–31 Jan. 2014. Iowa State Univ., Ames, IA. p. 26–28.

Monfreda, C., N. Ramankutty, and J.A. Foley. 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cycles 22 GB1022. doi:10.1029/. 2007GB002947

Monsanto. 2014. DeKalb corn: DKC57–75RIB Brand blend. Monsanto, St. Louis, MO.

Montgomery, D. R. 2007. Soil erosion and agricultural sustainability. Proc. Natl. Acad. Sci. U.S.A. 104:13268–13272.

Moore, A.D. 2014. The case for and against perennial forages in the Australian sheep-wheat zone: Modelling livestock production, business risk and environmental interactions. Anim. Prod. Sci. 54: 2029-2041 doi: 10.1071/AN14613Mueller, N.D., J.S. Gerber, M. Johnson, D.K. Ray, N. Ramankutty, and J.A. Foley. 2012. Closing yield gaps through nutrient and water management. Nature 490:254–257.

Ochsner, T.E., K.A. Albrecht, T.W. Schumacher, J.M. Baker, and R.J. Berkevich. 2010. Water balance and nitrate leaching under maize in a kura clover living mulch. Agron. J. 102:1169-1178.

Ojeda, J.J., O.P. Caviglia, J.G.N. Irisarri, and M.G. Agnusdei. 2018. Modelling inter-annual variation in dry matter yield and precipitation use efficiency of perennial pastures and annual forage crops sequences. Agr. Forest Meteorol. 259: 1-10 doi: 10.1016/j.agrformet.2018.04.014

Ordóñez, R.A., M.J. Castellano, J.L. Hatfield, M.J. Helmers, M.A. Licht, M. Liebman, R. Dietzel, R. Martinez-Feriaa, J. Iqbal, L.A. Puntel, S.C. Córdova, K. Togliatti, E.E. Wright, S.V. Archontoulis. 2018. Maize and soybean root front velocity and maximum depth in Iowa, USA. Field Crops Res. 215:122–131.

Page, E.R., M. Tollenaar, E.A. Lee, L. Lukens, and C.J. Swanton. 2009. Does the shade avoidance response contribute to the critical period for weed control in maize (*Zea mays*)? Weed Res. 49:563–571. doi:10.1111/j.1365-3180.2009.00735.x

Pembleton, K.G., B. R. Cullen, R. P. Rawnsley, M. T. Harrison, and T. Ramilan. 2016. Modelling the resilience of forage crop production to future climate change in the dairy regions of Southeastern Australia using APSIM. J. Agric. Sci. 154: 1131-1152.

Perfect, E., B.D. Kay, W.K.P. van Loon, R.W. Sheard, and T. Pojasok. 1990. Rates of change in soil structural stability under forages and maize. Soil Sci. Soc. Am. J. 54:179–186.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267:1117–1123.

Probert, M.E., J.P Dimes, B.A. Keating, R.C. Dalal, and W.M. Strong. 1998. APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agric. Syst. 56:1-28.

Puntel, L.A., J.E. Sawyer, D.W. Barker, R. Dietzel, H. Poffenbarger, M.J. Castellano, K.J. Moore, P. Thorburn, and S.V. Archontoulis. 2016. Modeling Long-Term Corn Yield Response to Nitrogen Rate and Crop Rotation. Front. Plant Sci. 7:1630.

Robertson, M.J., and P.S. Carberry. 1998. Simulating growth and development of soybean in APSIM. In: Proceedings Tenth Australian Soybean Conference: Brisbane, 15-17 September, pp. 130e136.

Robertson, W.K., H.W. Lundy, G.M. Prine, and W.L. Currey. 1976. Planting corn in sod and small grain residues with minimum tillage. Agron. J. 68:271–274.

Rogovska, N., D.A. Laird, and D.L. Karlen. 2016. Corn and soil response to biochar application and stover harvest. Field Crops Res. 187:96–106.

Tisdall, J.M., and J.M. Oades. 2006. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33:141–163.

Sainju, U.M., and A.W. Lenssen. 2011. Soil nitrogen dynamics under dryland alfalfa and durum–forage cropping sequences. Soil Sci. Soc. Am. J. 75:669-677.

Sawyer, J., E. Nafziger, G. Randall, L. Bundy, G. Rehm, and B. Joern. 2006. Concepts and rationale for regional nitrogen rate guidelines for corn (PM 2015). https://store.extension.iastate.edu/Product/pm2015-pdf Iowa State University Extension and Outreach, Ames, Iowa.

Schnepf, R. 2013. Renewable Fuel Standard (RFS): Overview and Issues. CRS Report No. R40155. Washington, DC: Congressional Research Service. https://www.fas.org/sgp/crs/misc/R40155.pdf (accessed 5 Apr 2017).

Scott, T.W., J. Mt. Pleasant, R.F. Burt, and D.J. Otis. 1987. Contribution of ground cover, dry matter, and nitrogen from intercrops and cover crops in a maize polyculture system. Agron. J. 79:792–798. doi:10.2134/agronj1987.00021962007900050007x

Snow, V.O., Huth, N.I., 2004. The APSIM MICROMET Module. HortResearch Internal Report No. 2004/12848. HortResearch, Auckland.

Teixeira, E.I., H.E. Brown, A. Michel, E. Meenken, W. Hu, S. Thomas, N.I. Huth, and D.P. Holzworth. 2018. Field estimation of water extraction coefficients with APSIM-Slurp for water uptake assessments in perennial forages. Field Crops Res. 222: 26-38 doi: 10.1016/j.fcr.2018.03.011

United Nations, Department of Economic and Social Affairs, Population Division. 2017. World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP/248.

USDA-NASS. 2018. Agricultural statistics data base (Quick Stats). USDA. http://www.nass.usda.gov/Quick_Stats/ (accessed 7 Mar 2018).

USDA-NASS. 2014. 2012 Census of Agriculture. http://www.agcensus.usda.gov/Publications/2012/#full_report

USDOE. 2011. U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. 227p.

Wallach, D. 2006. Evaluating crop models. In: D. Wallach et al., editors, Working with dynamic crop models: Evaluations, analysis, parameterization, and applications. Elsevier, Amsterdam. p. 11–53.

Wiggans, D.R., J.W. Singer, K.J. Moore, and K.R. Lamkey. 2012. Response of continuous maize with stover removal to living mulches. Agron. J. 104:917–925. doi:10.2134/agronj2011.0395

Wilhelm, W.W., J.M.F. Johnson, D.L. Karlen, and D.T. Lightle. 2007. Corn stover to sustain soil organic carbon further constrains biomass supply. Agron. J. 99:1665–1667.

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. 2004. Crop and soil productivity response to maize residue removal: A literature review. Agron. J. 96:1–17.

Wright, D., and Lenssen, A.W. 2013. Recognizing challenges to Iowa’s annual cropping systems. Agriculture and Environment Extension Publications. 186. http://lib.dr.iastate.edu/extension_ag_pubs/186

Xu, G, F. Xiaorong, and A.J. Miller. 2012. Plant nitrogen assimilation and use efficiency. Annu. Rev. Plant. Biol. 63:153-82.

Figure Captions (Headers & Footnotes)

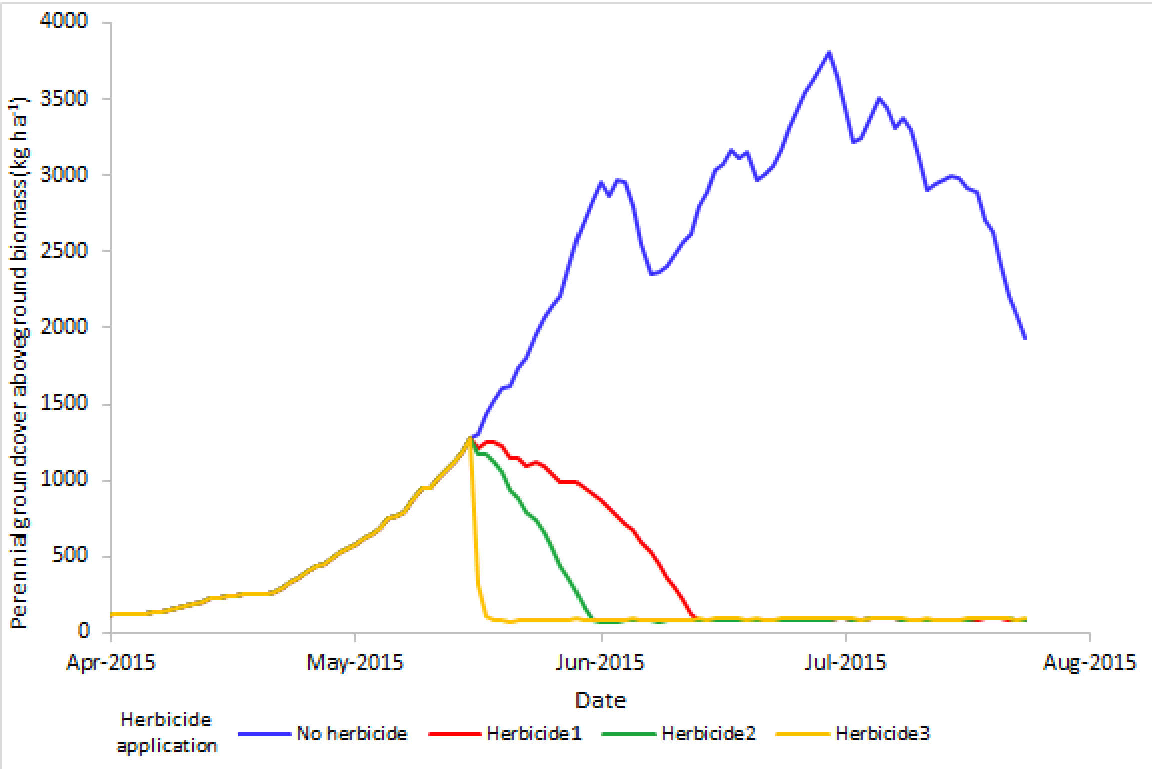

Figure 1. Perennial groundcover aboveground biomass accumulation on a dry matter basis (kg ha^{-1}) as affected by herbicide application effectiveness; scenarios included no herbicide application in blue, 7% of existing LAI killed per day in red (Herbicide1), 10% of existing LAI killed per day in green (Herbicide2), and 70% of existing LAI killed per day in yellow (Herbicide3).

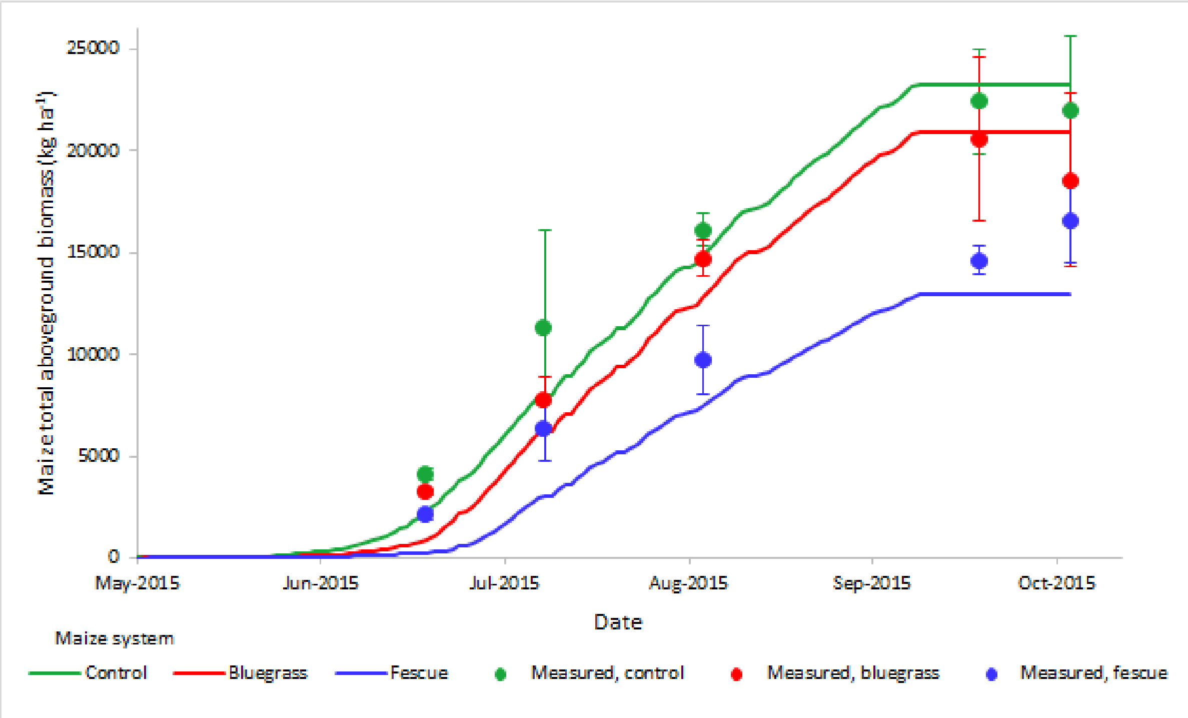

Figure 2. Simulated (lines) maize total aboveground biomass on a dry matter basis (kg ha^{-1}) for conventional maize with residue retention as the control, maize with intercropped Kentucky bluegrass, and maize with intercropped creeping red fescue. Simulations are based on measured values for maize total aboveground biomass on a dry matter basis (kg ha^{-1}) (points +/- SE) in a control, bluegrass, and fescue PGC system at five points during the maize growing season **in 2015 at Boone, IA**.

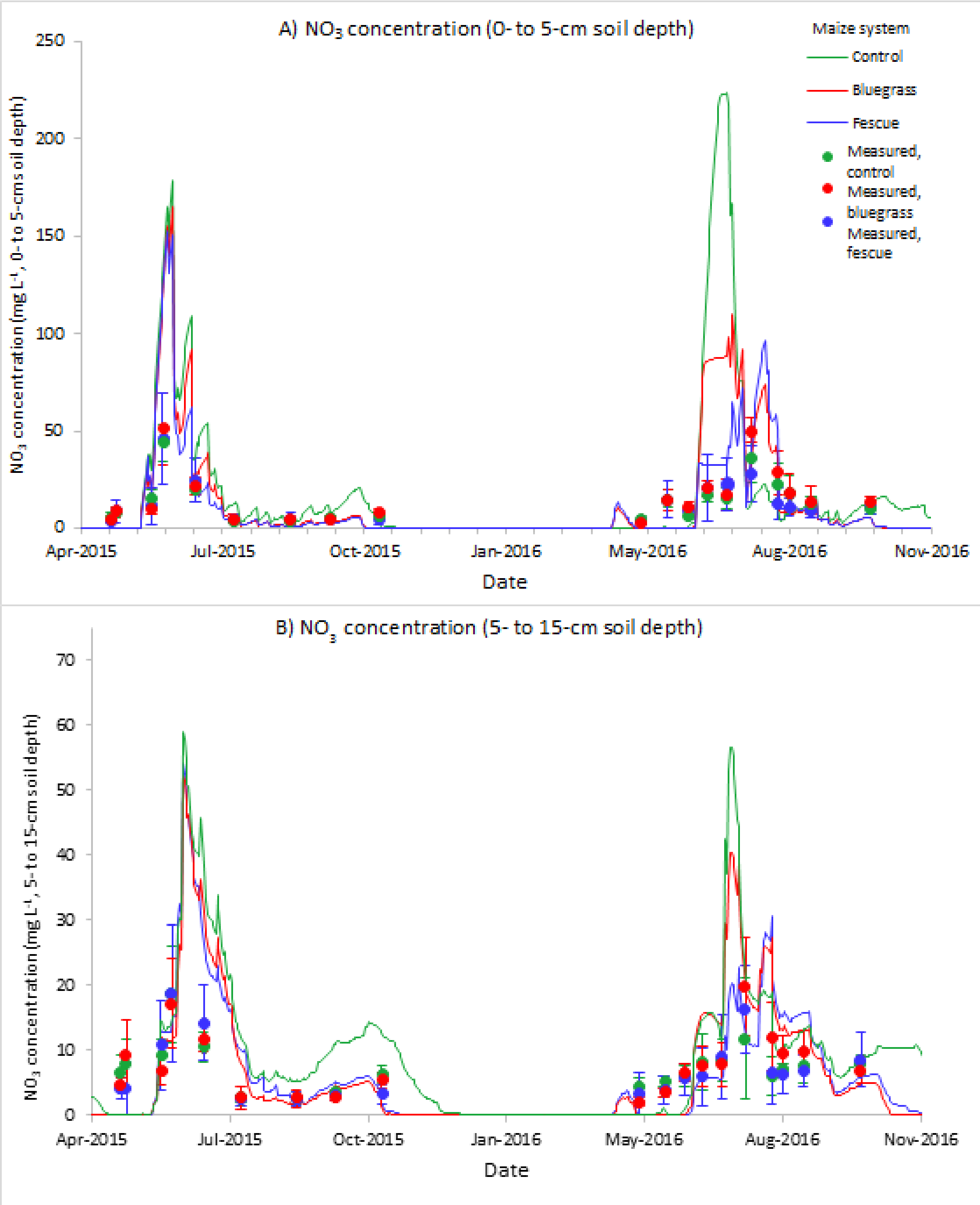

Figure 3. Simulated (lines) soil nitrate (NO_3) concentration (mg L^{-1}) (points +/- SE) in (A) 0- to 5-cm soil depth and (B) 5- to 15-cm soil depth under three studied treatments (conventional maize with residue retention as the control, maize intercropped with perennial bluegrass, and maize intercropped with perennial fescue) over three years (2014, 2015, and 2016) at Boone, IA. Simulations are based on measured values for soil NO_3

concentration (mg L^{-1}) (points +/- SE) in a control, bluegrass, and fescue PGC system collected during 2014, 2015, and 2016 at Boone, IA.

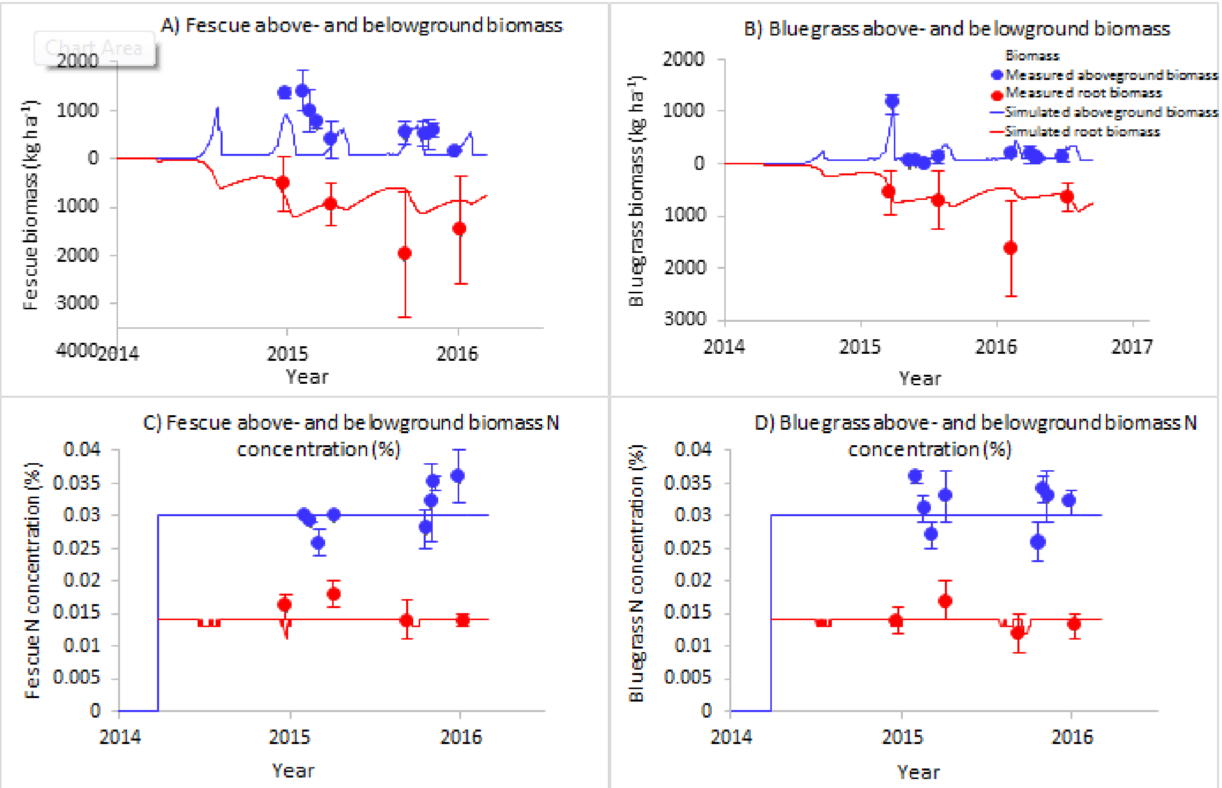

Figure 4. Simulated (lines) above- and belowground perennial groundcover biomass (kg ha^{-1}) **for (A) fescue and (B) Kentucky bluegrass over three years (2014, 2015, and 2016) at Boone, IA. Simulated (lines) N concentration (%) in above- and belowground perennial groundcover biomass in (C) fescue and (D) Kentucky bluegrass over three years (2014, 2015, and 2016) at Boone, IA.** Simulations are based on measured values for **above- and belowground perennial groundcover biomass** (kg ha^{-1}) and N concentration (%) (points +/- SE) in a control, bluegrass, and fescue PGC system collected during 2014, 2015, and 2016 at Boone, IA.

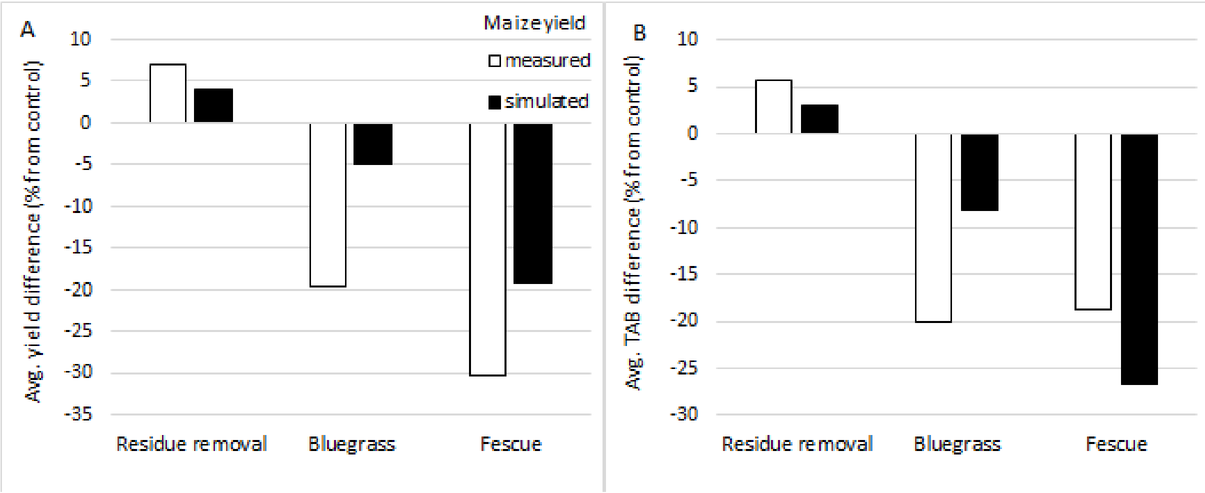

Figure 5. (A) Difference between simulated and measured maize grain yield (kg ha^{-1}) as a percent and (B) difference between simulated and measured maize TAB (kg ha^{-1}) as a percent from conventional maize with residue retention as the control for the measured and simulated maize with residue removal, maize with residue removal and intercropped Kentucky bluegrass, and maize with residue removal and intercropped creeping red fescue over three years (2014, 2015, and 2016) at Boone, IA.

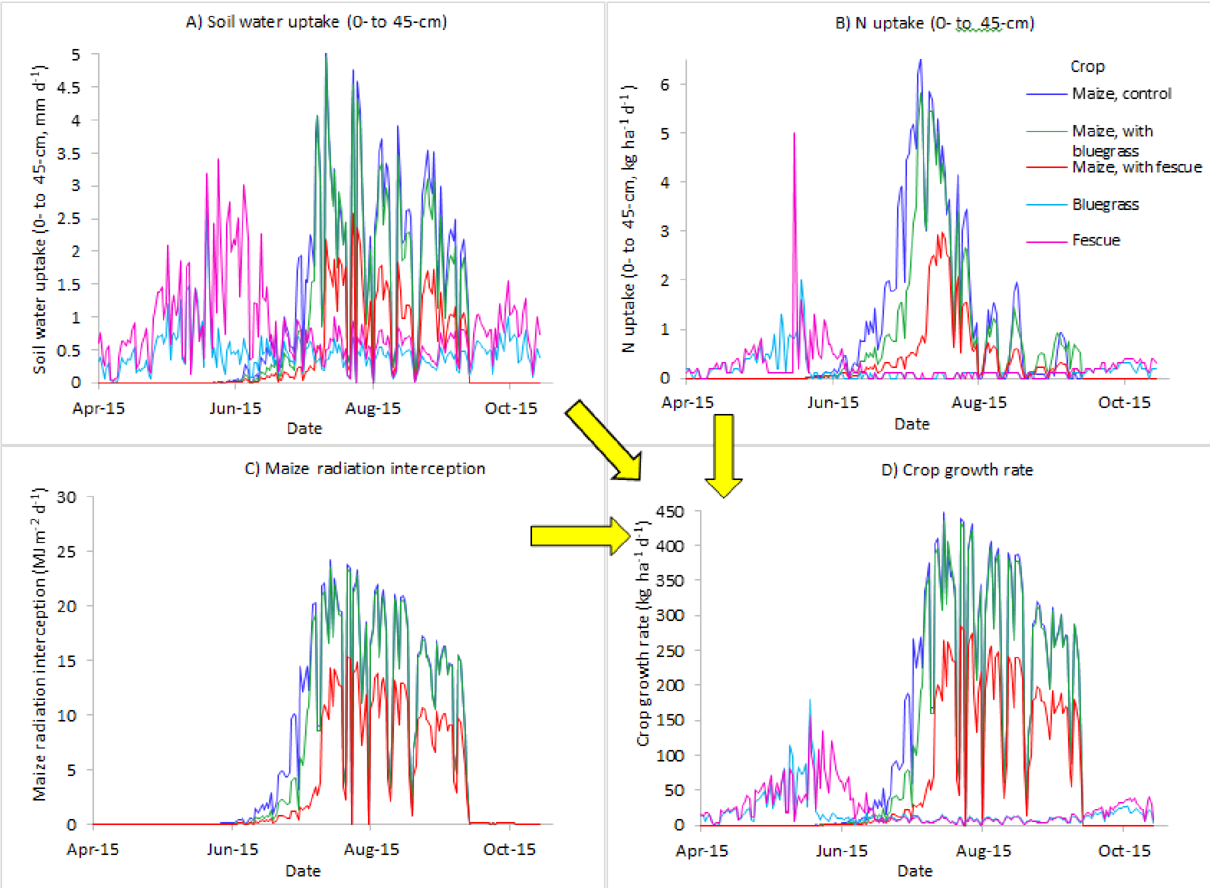

Figure 6. Simulated values (lines) for (A) soil water uptake (0- to 45-cm soil depth), (B) N uptake (0- to 45-cm soil depth), (C) maize radiation interception (MJ m^{-2} d^{-1}) and (D) crop growth rate (kg ha^{-1} d^{-1}) for conventional maize with residue retention as the control, maize with intercropped Kentucky bluegrass, and maize with intercropped creeping red fescue in (A), (B), (C), and (D), with Kentucky bluegrass and creeping red fescue additionally in (A), (B), and (D).

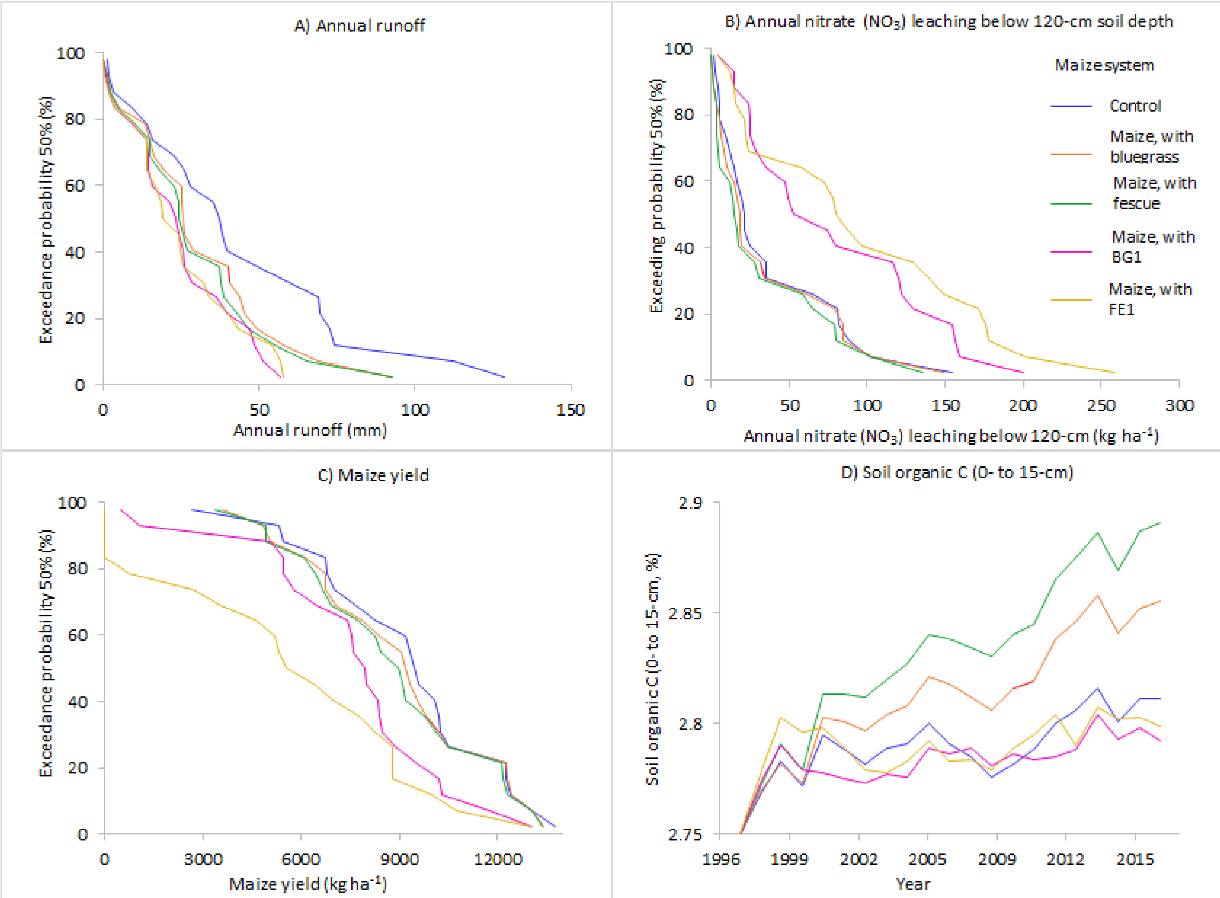

Figure 7. Simulation results reflecting the probability of (A) runoff, (B) leaching, (C) yield, and (D) soil organic carbon under five treatments (control, continuous maize with residue retention and no perennial cover, planted 16 May every year; bluegrass, maize with intercropped Kentucky bluegrass and herbicide effectiveness of 0.5 and suppression period of 10 May to 5 Sept.; fescue, maize with intercropped creeping red fescue and herbicide effectiveness of 0.5 and suppression period of 10 May to 5 Sept.; BG1, maize with intercropped Kentucky bluegrass and herbicide effectiveness of 0.5 and suppression period of 5 June to 25 Aug.; and FE1, maize with intercropped creeping red fescue and herbicide effectiveness of 0.5 and suppression period of 5 June to 25 Aug.).

Table 1. Treatments for the maize, maize following maize (MM), and maize following two years of maize (MMM) sequences at Boone in 2014, 2015, and 2016, respectively, with residue removal protocol exclusively for the MM and MMM sequences.

Treatment	Groundcover	Tillage method	Residue removal	N fertilizer application
1	None	Conventional	Removed	Broadcast
2	None	Conventional	Not removed	Broadcast
3	Bluegrass	Zone tillage	Removed	Banded
4	Fescue	Zone tillage	Removed	Banded

Table 2. Original and revised (new) APSIM parameter values. Original parameter values represent maize values in existing APSIM simulations. New input values represent adjusted cultivar-specific parameters.

Parameter	Original Value	New Value
Thermal time from emergence to end juvenile (°C-days)	214	250
Thermal time from flowering to maturity (°C-days)	885	815
Potential kernel number per ear (No.)	800	800
Potential kernel growth rate (g kernel^{-1} d^{-1})	9.17	6.77
Thermal time from flowering to start grain fill (°C-days)	150	170

Table 3. Original and revised (new) APSIM parameter values. Original parameter values represent warm season C4 bambatsi in existing APSIM simulations. New input values represent cool season C3 Kentucky bluegrass and creeping red fescue.

Parameter	Original Value	New Value
Light extinction	0.7	0.37
Stem allocation	0.6	0.23
Frost stress (0,1, in °C)	(0,2)	(-14,2)
Photoperiod (daylight hours (0,1))	(12.5,13.5)	(10.5,13.5)
Maximum leaf senescence rate	0	0.2
Root N concentration (g g^{-1})	0.01	0.014
RUE (bluegrass only, g MJ^{-1})	2.0	1.5
Max root depth (cm)	200	46

Table 4. Means of five 20-year randomized runs for the runoff (mm), maize yield (kg ha^{-1}), and N leaching (kg ha^{-1}) at 50% probability (one 31 Dec. 2006) for the control and percent change for four other treatments (continuous maize with residue retention and no perennial cover, planted 16 May every year; Bluegrass, maize with intercropped Kentucky bluegrass and herbicide effectiveness of 0.5 and suppression period of 10 May to 5 Sept.; Fescue, maize with intercropped creeping red fescue and herbicide effectiveness of 0.5 and suppression period of 10 May to 5 Sept.; BG1, maize with intercropped Kentucky bluegrass and herbicide effectiveness of 0.5 and suppression period of 5 June to 25 Aug.; and FE1, maize with intercropped creeping red fescue and herbicide effectiveness of 0.5 and suppression period of 5 June to 25 Aug.).

Treatment	Runoff (mm)	Maize grain yield (kg ha^{-1})	N leaching (kg ha^{-1})	Soil organic C (0-15 cm)
Control	37.6	9457	21.1	2.79
		Percent change (%) from the control		
BG	-31	-3	-14	1.0
FE	-35	-5	-30	1.7
BG1	-37	-16	152	-0.2
FE1	-48	-41	281	-0.3